

# Tunneling Studies of Pseudogaps: a Comment

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The recent observation of the pseudogap in tunneling measurements on  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  [1–3] should prove of great value in unravelling the mysteries of the ‘normal state’ of the cuprates. However, several issues in these papers require clarification. Here, we discuss two important points.

First, the gaps observed in the quasiparticle tunneling spectra are assumed to be superconducting gaps, and taken as evidence that the pseudogap is caused by superconducting fluctuations. However, a normal-state gap (due, e.g., to charge or spin density waves) will also show up in the tunneling spectra [4]. For illustrative purposes, we use the pinned [5] Balseiro-Falicov (BF) [6] model of competition between a charge density wave (CDW) and (s-wave) superconductivity (SC), which gives a good account of the doping dependence of the pseudogap [7] and is a simple model for striped phases [8]. For a pure CDW, the spectral function is of BCS form:

$$A(k, \omega) = 2\pi[u_k^2\delta(\omega - E_{k+}) + v_k^2\delta(\omega - E_{k-})], \quad (1)$$

with  $u_k^2 = 1 - v_k^2 = (1 + \epsilon_{k-}/\tilde{E}_k)/2$ ,  $E_{k\pm} = (\epsilon_{k+} \pm \tilde{E}_k)/2$ ,  $\epsilon_{k\pm} = \epsilon_k \pm \epsilon_{k+Q}$  and  $\tilde{E}_k = \sqrt{\epsilon_{k-}^2 + 4G_k^2}$ , where the nesting vector  $Q = (\pi, \pi)$ , and the gap  $G_k$  and dispersion  $\epsilon_k$  are defined in Refs. [5,6]. Figure 1 shows the calculated phase diagram and the net low-T tunneling gap, defined as half the peak-peak separation. The inset shows that in the mixed CDW-superconducting state a single gap evolves in the calculated tunneling density of states  $\rho(E)$  (except for phonon structure). The tunneling peaks coincide with the split electronic energy dispersion near  $(\pi, 0)$  and  $(0, \pi)$  of the Brillouin zone. These calculations demonstrate that a normal state pseudogap will show up in the tunneling spectra. This normal state gap need not be associated with a CDW, but could be a flux phase [9], spin density wave [10], or some more exotic phase.

All three papers [1–3] report a prominent dip in the tunneling spectrum near twice the gap energy, suggested to be associated with an energy threshold for quasiparticle decay. Such a decay channel should be mainly sensitive to the tunneling density of states, regardless of the nature of the pseudogap.

Renner, et al. [1] state that ‘the pseudogap is centered at the Fermi level in both under- and overdoped samples. It is therefore unlikely that the pseudogap results from a band structure effect.’ This statement assumes that

doping is accomplished by a rigid band filling. However, it has been repeatedly observed that *strong correlations pin the Fermi level to a Van Hove singularity (VHS) over an extended doping range* [11]. In the calculations of Fig. 1, the Fermi level was assumed pinned to the VHS for doping up to  $x=0.125$ , with a fixed VHS and rigid band filling at higher doping, to simulate these effects.

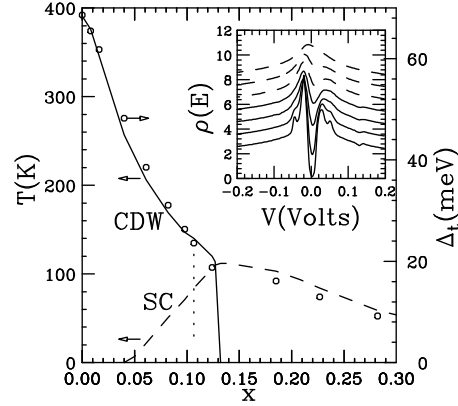


FIG. 1. Phase diagram of pinned Balseiro-Falicov model. Circles = net tunneling gap,  $\Delta_t$ . Inset: Tunneling spectra of a density-wave superconductor, using parameters of dotted line in main frame. Temperatures (from top to bottom) = 130, 110, 90, 80, 70, 50, and 30 K (dashed lines: T above the superconducting transition temperature).

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